5.5.2.5 Ellipsat Becomes Operational

Iridium and AMSC system capacities are unaffected from what is shown in Section 5.5.1. Globalstar and Odyssey must interference share with Ellipso-2. Like Odyssey, it is assumed that Ellipsat would take full advantage of the 8.5 MHz available for its use each in the L- and S-bands.

Globalstar, Odyssey and Ellipsat operate with capacities and spectral efficiencies as calculated in Section 5.4.

Using the formulas from Section 5.2 and only considering the CONUS, these systems generate the following capacity:

Table 5.5.2-3

System Channels	Spectrum	Channels
Globalstar	7.5 MHz (L) 7.5 MHz (S)	768
Iridium	5.5 MHz (L)	2556
AMSC	2.75 MHz (L) 2.75 MHz (S)	217
Odyssey	8.25 MHz (L) 8.25 MHz (S)	687
Ellipsat	8.25 MHz (L) 8.25 MHz (S)	405
Total	16.5 MHz (L) 11.0 MHz (S)	4633
Spectral Efficiency (Channels per MHz)		168

5.5.2.6 Constellation Becomes Operational

Iridium and AMSC system capacities are unaffected from what is shown in Section 5.5.1. Globalstar, Odyssey, and Ellipsat must interference share with Constellation. Like Odyssey and Ellipsat, it is assumed that Constellation takes full advantage of the 8.5 MHz available for its use each in the L- and S-bands.

Globalstar, Odyssey, Ellipsat,and Constellation operate with capacities and spectral efficiencies as calculated in Section 5.4.

Using the formulas from Section 5.2 and only considering the CONUS, these systems generate the following capacity:

Table 5.5.2-4

System Channels	Spectrum	Channels
Globalstar	7.5 MHz (L) 7.5 MHz (S)	671
Iridium	5.5 MHz (L)	2556
AMSC	2.75 MHz (L) 2.75 MHz (S)	217
Odyssey	8.25 MHz (L) 8.25 MHz (S)	600
Ellipat	8.25 MHz (L) 8.25 MHz (S)	354
Constellation	8.25 MHz (L) 8.25 MHz (S)	239
Total	16.5 MHz (L) 11.0 MHz (S)	4637
Spectral Efficiency (Channels per MHz)		168

5.5.2.7 <u>Celsat Becomes Operational</u>

Iridium and AMSC system capacities are unaffected from what is shown in Section 5.5.1. Globalstar, Odyssey, Ellipsat, and Constellation must interference share with Celsat. Like Odyssey, Ellipsat, and Constellation, it is assumed that Celsat takes full advantage of the 8.5 MHz available for its use each in the L- and S-bands.

Globalstar, Odyssey, Ellipsat, Constellation, and Celsat operate with capacities and spectral efficiencies as noted in Section 5.4.

Using the formulas from Section 5.2 and only considering the CONUS and Puerto Rico, these systems generate the following capacity:

Table 5.5.2-5

System Channels	Spectrum	Channels
Globalstar	7.5 MHz (L) 7.5 MHz (S)	596
Iridium	5.5 MHz (L)	2556
AMSC	2.75 MHz (L) 2.75 MHz (S)	217
Odyssey	8.25 MHz (L) 8.25 MHz (S)	530
Ellipsat	8.25 MHz (L) 8.25 MHz (S)	314
Constellation	8.25 MHz (L) 8.25 MHz (S)	212
Celsat	8.25 MHz (L) 8.25 MHz (S)	1874
Total	16.5 MHz (L) 11.0 MHz (S)	6299
Spectral Efficiency (Channels per MHz)		229

Annex 5.1: Derivation of CDMA Uplink Capacity with Interference Sharing

1. INTRODUCTION

Satellite cellular systems can utilize the same frequency with classical band segmentation techniques or with a co-frequency/co-location interference sharing strategy. Interference sharing is well suited to systems such as Cod-Division Multiple Access (CDMA) which use code sequences to provide robustness against interference from other users, whether they are from the same or different systems. An interference sharing rule [1] has been proposed for Mobile Satellite Services (MSS) in an uplink band from 1610-1626.5 MHz and a downlink band from 2483.5-2500 MHz. In this report the uplink capacity of interference-shared CDMA systems is derived. The analysis specifically considers the effect of voice activity, beam overlap, average fade margin and earth terminal dynamic range in the derivation. A first order shadowing model is used to determine the effect on capacity. A normalized multiple-access-interference (MAI) term z is introduced which include the effects of voice activity, beam overlap and average fade margin, as factors. The result shows that each system has a beam capacity which is inversely proportional to the normalized MAI. The uplink capacity under an interference sharing rule can be limited by dynamic range if the transmit terminal ratio of maximum to average power is less than the additional power required to overcome certain shadowing criteria. In satellite cellular systems, the adaptive power control system must compensate for an attenuation component $1/\alpha$ and a modem degradation component s. For a fixed shadowing criteria of α and s, the effects of sharing are to increase interference and reduce uplink terminal dynamic range. Link analysis of proposed CDMA systems is used to derive the dynamic range parameter and the capacity equation derived herein is used to illustrate the effect of this parameter under interference sharing rules.

2. CHANNEL CAPACITY FOR CDMA UPLINKS

2.1 Capacity Definition

The channel capacity is defined here in bits/second/Hz per satellite antenna beam, i.e.,

$$\eta = \frac{N_u R_b}{W} \frac{1}{N_c} \qquad \textit{bits/second/Hz/beam}$$

(2.1)

where

N_u = number of users per antenna beam

R_b = user information rate in bits/second

W = channel bandwidth in Hz

Nc = number of beams in a frequency re-use cluster

The antenna beam from the satellite defines a "cell" on the ground. Cellular communication systems increase capacity by re-using the available frequency band in groups or clusters of cells. The smaller the cluster size N_C the greater the frequency re-use and correspondingly, the channel capacity. For a satellite, the frequency re-use factor, $F_R = N_B/N_C$, where N_B is the number of antenna beams per satellite, is used to define the effectiveness of frequency re-use. The satellite capacity is then

$$C_{SAT} = N_B \eta = \frac{N_u R_b}{W} F_R$$

(2.2)

CDMA systems use pseudo-noise codes to provide protection against interference from users within a cell and from users in adjacent cells. This feature allows for system operation with cell cluster sizes as small as unity, i.e., frequency re-use in every cell. For the CDMA capacity calculation here we assume a cluster size N_c of unity.

The capacity calculation derived in this note will consider the effect of shadowed and fading users to first order. A slow adaptive power control is assumed in this model. The power control system can not track all fades instantaneously because of satellite delay. For more rapid fading the adaptive power control must provide some additional power to compensate for the degraded modem performance under fading rather than non-fading conditions. It is assumed that the adaptive power control correctly adjusts the average power to compensate for the attenuation component associated with shadowed conditions. On the uplink within a single system the attenuation component and the power control correction cancel each other out so that the average power at the satellite is unchanged. Any increase in power is due to the degradation component of the power control system. Without defining specific values, we denote in this first order model, a fraction β of shadowed users which because of the fast fading require a degradation compensation of 10 LOG (s) dB. Of course in an actual application there would be a range of values for the degradation compensation depending on the type of fading, Rayleigh or Rician, the fading speed and the coding provided. The use of a single value is a first order approximation.

2.2 Normalized Multiple Access Interference (NMAI)

In an asynchronous system the interference seen by a single user is

$$I_0 = \frac{vE_bR_b}{W}\left[(1-\beta)\,(N_u-1) + \beta(N_u-1)s + I_AN_u\right] \tag{2.3}$$

where

E_b = energy per information bit

v = voice activity factor, $v \leq 1$

β = fraction of users compensated for degradation

s = degradation compensation factor, $s \geq 1$

I_A = adjacent cell interference

We define a single user normalized-multiple-access-interference (NMAI) term which for $N_u >> 1$ is approximately

$$z = v\,(1-\beta + \beta s + I_A) \qquad \textit{NMAI} \tag{2.4}$$

so that the total interference is

$$I_0 = \frac{N_uE_bR_b}{W}z = \eta E_bz \tag{2.5}$$

Note that attenuation compensation to correct for average signal loss due to fading or shadowing does not increase the multiple-access-interference (MAI). On the other hand, additional power provided to compensate for degradation increases the multiple-access-interference by the addition of the term $v\beta s$. Thus the CDMA system should be designed to select how many users will be compensated in order not to reduce capacity to too small a level. In a practical system, the base station can monitor both the received power and the short term BER received on the reverse link. These two measurements allow for resolution of the attenuation and degradation components. The mean fading effect should always be corrected and the system decides the fraction, β, of shadowed users that should be degradation compensated with an augmentation factor $s > 1$. It turns out that for small outage probability on the order of 1%, the fraction of compensated users must be close to the number of shadowed users which are present. Thus in this model we will use β to represent the mean value of shadowed users. For the adjacent cell interference, we have

$$I_A(\beta_s) = I_A(0)\,(1-\beta_s + s\beta_s) \tag{2.6}$$

where $I_A(0)$ is the normalized adjacent cell interference when there is no compensation for shadowed users. This interference can be calculated by considering a multi-cell structure with N_1 adjacent cells and N_2 next-to-adjacent cells with attenuations values A_1 and A_2, respectively. Thus

$$I_A(0) = N_1A_1 + N_2A_2$$

Values for A_1 and A_2 were obtained in [2] by approximating measured circular beam antenna patterns by Gaussian functions and calculating the average coupling effect. Integration of theoretical or measured antenna patterns can also be used to calculate the adjacent cell interference $I_A(0)$. The normalized multiple-access-interference can now be written as

$$z = vB_{OF}\, f_u \tag{2.7}$$

where

$$B_{OF} = (1 + I_A(0)) \tag{2.7a}$$

is the beam overlap corresponding to the ratio of total interference power from all beams relative to a single beam and

$$f_u = 1 - \beta + \beta s \tag{2.7b}$$

is the uplink average fade margin for a single system.

2.3 Infinite Dynamic Range

We first consider an ideal system where there is no limit on the transmit terminal power. Now that the NMAI z has been defined we can return to Eq. (2.5) and derive the infinite dynamic range capacity as a function of the multiple-access-interference. Adding the additive noise spectral density to Eq. (2.5), we have

$$N_0 + I_0 = N_0 \, (1 + \eta z E_b / N_0)$$

The modem effective signal-to-noise ratio (SNR) for a non-faded user is defined as

$$y = \frac{E_b}{N_0 + I_0} = \frac{E_b/N_0}{1 + \eta \, z E_b/N_0} \tag{2.8}$$

Let $x = E_b/N_0$ be the signal-to-noise ratio under no fading conditions and one can then solve for the CDMA channel capacity (note N_c has been chosen as unity)

$$\eta = \left(\frac{1}{y_c} - \frac{1}{x}\right) / z \tag{2.9}$$

The critical modem SNR is set at a level to provide the nominal clear air quality of service. The channel capacity for a CDMA system is dependent on the critical modem SNR in a non-fading environment and is dependent on the NMAI term z. Since fading effects are compensated for by the adaptive power control system, their effect on capacity is limited to the increase in multiple-access-interference due to the degradation component s in the average fade margin factor f_u.

3. INTERFERENCE SHARING

3.1 Sharing Model

An interference sharing rule [1] for mobile satellite services has been proposed. This rule would allocate a fixed amount of interference power spectral density at a satellite receiver to each satellite system. Under conditions of a uniform distribution of point emitters each with the same radiated power intensity, the allocated interference level is independent of the path loss L to the satellite and the satellite antenna gain G_s. The important result first developed by Mallinckrodt [4] is repeated here for convenience to the reader.

For an areal density of uniform brightness, ε_s,W/M^2/Hz the total effective isotropic interference power spectral density, β_s, radiated from the satellite footprint is

$$\beta_s = \epsilon_s A_f \tag{3.1}$$

where A_f is the footprint area on the surface of the earth illuminated by an antenna of gain G_s. The gain of an antenna is the ratio of the surface area of a sphere at a distance R from the antenna divided by the area illuminated. Thus

$$G_s = 4\pi R^2 / A_f \tag{3.2}$$

The interference power spectral density at the satellite is then

$$I_s = \beta_s G_s / L_s = 4\pi \beta_s R^2 \epsilon_s / L \tag{3.3}$$

where L is the path loss

$$L = (4\pi R)^2/\lambda^2 \tag{3.4}$$

In Equation (3.3) the satellite gain and R^2 loss factors are cancelled to obtain

$$I_s = \epsilon_s \lambda^2/4\pi = \epsilon_s / G_1 \tag{3.5}$$

where G_1 is the gain of an ideal $1m^2$ antenna. The consequence of (3.5) is that an allocation of source interference density translates directly into the same allocation of interference density at the satellite receiver independent of satellite height and satellite antenna gain. It is often convenient to reference the allocated source interference relative to the satellite antenna noise kT_e where T_e is the noise temperature due to earth radiation. Using Equation (3.5) for the noise radiation we have

$$I_N = kT_e = \epsilon_N / G_1 \tag{3.6}$$

For example at the center of the MSS uplink portion of the L-band and with a noise temperature of 500°K, we have

$$f = 1618.25 \text{ MHz}$$

$$10\,\mathrm{LOG}(G_1) = 25.5 \text{ dB}$$

$$k = 1.38\text{ E-23 W/Hz/K}$$

and $$\varepsilon_N = -176.1 \text{ dBW/m}^2\text{/Hz}$$

(3.7)

The interference sharing rule [1] allocates a value of source interference density ε_s for each system.

3.2 Single System Capacity

The CDMA capacity equation derived in Equation (2.9) includes a value x for the user E_b/N_0 value. When the interference at the receiver of the satellite is fixed by a rule such as defined in the previous subsection, how is the capacity equation modified? By the definition of the normalized multiple-access-interference term z, the interference density at the satellite receiver is

$$I_s = E_b \eta z$$

(3.8)

For an allocated source interference density ε_s, we have from Equation (3.5)

(3.9)

$$\epsilon_s = I_s G_1 = E_b G_1 \eta z$$

and the equvalent thermal noise density is

$$\epsilon_N = G_1 k T_e = G_1 N_0 \tag{3.10}$$

where N_0 is the noise density at the receiver input. The E_b/N_0 value in Equation (3.12) is then expressed in terms of the normalized source interference allocation $\varepsilon_s/\varepsilon_N$ as

$$x = E_b/N_0 = \epsilon_s/\epsilon_N \eta z \tag{3.11}$$

After simple algebra, the CDMA capacity equation becomes

$$\eta = \frac{\epsilon_s}{\epsilon_N + \epsilon_s} (1/y_A z) \tag{3.12}$$

3.3 Multiple System Capacity

3.3.1 Modification of Average Fade Margin Equation

In a single system, the increase in transmit power to overcome uplink attenuation is not seen by the satellite receiver. In multiple systems this attenuation may or may not increase the multiple-access-interference at another satellite. Thus the average fade margin expression Equation (2.7b) is not valid for multiple systems. The multiple system model should also consider the type of adaptive power control compensation. For fixed users, the power control system can track the instantaneous fades and the mean compensation is equal to "α" the attenuation component of the shadowing process. For mobile users who are shadowed, the compensation includes two factors, the attenuation "α" and the degradation compensation "s". The latter factor mitigates the short term fading effect.

In Table 3.1 the four combinations if shadowing are illustrated for a source and victim satellite. The probability of shadowing is taken as β and mobile and fixed shadowed users are considered equally likely. Note that when the victim is shadowed, the multiple-access-interference is reduced. The average fade margin for multiple systems using interference sharing is then

$$F_u = (1-\beta)^2 + (1-\beta)\alpha\beta(1+s)/2 + (1-\beta)\beta/\alpha + \beta^2(1+s)/2 \tag{3.13}$$

The normalized MAI for multiple systems is then

$$z = vB_{OF}F_u$$

Table 3.1

Average Fade Margin Model, Multiple Systems

	$p = 1-\beta$ SOURCE SHADOWED	$P = \beta$ SOURCE UNSHADOWED
$p = (1-\beta)$ VICTIM UNSHADOWED	1	αs or α
$P = \beta$ VICTIM SHADOWED	$1/\alpha$	s or 1

β = fraction of shadowed users

α = attenuation compensation

s = degradation compensation

Mobile users require mean compensation = αs $p = \beta/2$

Fixed users require mean compensation = α $p = \beta/2$

(Mobile and fixed shadowed users are equally likely)

3.3.2 Capacity Formula for Multiple Systems

3.3.2.1 No Dynamic Range Restriction

If system p is allocated a source interference density ϵ_{sp}, the total interference density allocated for P systems is

$$\epsilon_{sT} = \sum_{p=1}^{P} \epsilon_{sp} \tag{3.15}$$

The normalized interference seem by the satellite receiver in any of the system is

$$\frac{I_T}{N_0} = \frac{\epsilon_{sT}}{\epsilon_N} \tag{3.16}$$

The pth system requires an effective signal-to-noise ratio given by

$$y_{A_p} = \frac{E_{bp}}{N_0 + I_T} = \frac{E_{bp}/N_0}{1 + \epsilon_{sT}/\epsilon_N} \tag{3.17}$$

Using Eq. (3.9) to relate the user signal-to-noise ratio at the satellite to the allocated source interference density, one has

$$\epsilon_{sp} = E_{bp} G_1 \eta_p z_p \tag{3.18}$$

where in general, different systems may not have the same bit energy, normalized MAI, or capacity.

Since $\varepsilon_{sn} = G_1 N_0$, we have an expression in terms of the individual system capacity, viz.,

$$y_{Ap} = \frac{\epsilon_{sp}/(\epsilon_N \eta_p z_p)}{1 + \epsilon_{sT}/\epsilon_N} \tag{3.19}$$

and for solving the pth system capacity

$$\eta_p = \frac{\epsilon_{sp}}{\epsilon_N + \epsilon_{sT}} \frac{1}{y_{Ap} z_p} \tag{3.20}$$

For the special case where the interference allocation is equally divided among the P systems, the total capacity for a system allocation ε_s is

$$\eta_T = \sum_{p=1}^{P} \eta_p = \frac{\epsilon_s}{\epsilon_N + P\epsilon_s} \sum_{p=1}^{P} (1/y_{Ap} z_p) \tag{3.21}$$

Clearly each system maximizes its capacity by minimizing the required modem signal-to-noise ratio and normalized multiple-access-interference.

3.3.2.2 Dynamic Range Effects

In determining the capacity in the previous subsection, there is an implicit assumption that the shadowed users can be compensated for their attenuation and degradation factors. This compensation capability is a function of the earth terminal dynamic range and the interference noise floor established by other users in the CDMA environment.

For the shadowed user who is experiencing an attenuation of $1/\alpha$, i.e. the average signal power is reduced by the factor α, the required signal-to-effective noise ratio is

$$y_s = s y_A = \frac{\alpha E_b F_{DR}}{N_0 + I_0} \tag{3.22}$$

where s is the degradation compensation factor and F_{DR} is the earth terminal dynamic range ratio. Of interest here is handset operation where this dynamic range is limited either by peak power constraints or a safety standard [3]. If E_{bmax} is the maximum realizable value of bit energy at the receiver, the dynamic range for power increase to account for interference sharing and to leave sufficient additional range for the (α, s) shadowing objective is

$$D = \alpha E_{bmax} / s E_b \tag{3.23}$$

where E_b is the bit energy at the receiver for a clear sky user with no interference sharing. We assume that the system is designed such that $D \geq 1$, i.e. there is sufficient dynamic range to meet or exceed shadowing objectives when there is no interference sharing.

For simplicity of presentation, the derivation of the capacity under a dynamic range constraint is given for an equal allocation of source interference density for each system. The extension of the more general unequal allocation case is obvious.

Since there is no dynamic range limitation for a single system with no interference sharing, the single system capacity is given by Eq.(3.20) as

$$\eta(1) = \frac{\epsilon_s}{\epsilon_N+\epsilon_s}\,\frac{1}{y_A z} \tag{3.24}$$

The required signal-to-effective noise ratio for a clear sky user in a system sharing interference with P - 1 other systems is

$$y_A = \frac{\lambda E_b/N_0}{1+(P-1)\epsilon_s/\epsilon_N + \lambda E_b \eta(P) z/N_0} \tag{3.25}$$

where the last term in the denominator uses Eq.(3.8) to obtain the self interference contribution. The factor $\gamma \geq 1$ is the increase over the single system received bit energy in order to adjust for the increased interference power due to sharing. When there is adequate dynamic range so that the allocated interference density can be achieved, the capacity is given by Eq.(3.20). This condition is satisfied when

$$D E_b \eta(P) z/N_0 \geq \epsilon_s/\epsilon_N$$

and since

$$\eta(1)\, zE_b/N_0 = \epsilon_s/\epsilon_N$$

(3.26)

we have

$$\eta(P) = \frac{\epsilon_s}{\epsilon_N + P\epsilon_s}\ \frac{1}{yz} \qquad IF \quad D \geq \eta(1)/\eta(P)$$

(3.27)

If Eq.(3.27) is not valid, i.e. there is sufficient dynamic range to meet the source interference allocation, then $\gamma = D$ and one solves Eq.(3.25) for the capacity $\eta(P)$. Note that Eq.(3.26) should be used to convert E_b/N_0 in the solution. The answer is

$$\eta_D(P) = \frac{\eta(1)}{D}\,[D-P+1+(D-1)\epsilon_N/\epsilon_s]\ ,\ \eta_D(P) \geq 0$$
$$D \leq \eta(1)/\eta(P)$$

(3.28)

The subscipt D is used to denote the capacity when the augmentation factor γ is at the maximum value equal to D.

ANNEX 5.2

Capacity Calculation Tables and Link Analyses

This Annex contains the uplink CDMA analysis for three PFD values, -140, -143, and -146, in Tables 2.1, 2.2, and 2.3 respectively. These tables show the system parameters at the top of the table and the results of the calculation at the bottom. For two or more systems the capacity is given in two separate rows. The upper row contains the capacity number when there is no dynamic range limitation. The lower row does not apply if it is blank and is the dynamic range limited value otherwise. The dynamic range limited value is less than or equal to the unlimited value. The margin ratio rows represent the excess margin as a ratio relative to the required maximum margin of 8 dB. At the value of margin ratio of unity, there is no excess margin and dynamic range effects come into play.

Tables 2.4-8 are the link analysis calculations for the systems, ARIES, ELLIPSO, GLOBALSTAR, ODYSSEY and CELSTAR, respectively. As a function of the power flux density, the maximum average fade margin is determined from these analyses. The analyses also serve as a check on the capacity equation for a fixed PFD and also they illustrate the reduction in capacity required when there is insufficient margin.

Table 2.9 is the capacity analysis using the parameter set provided by the CDMA applicants assuming no dynamic range limitations.